SCOTS Application to Convex Aspheres

Cormic Merle; Exelis, Inc.
Peng Su, Ph.D.; University of Arizona

August 1, 2012

Principles of Operation

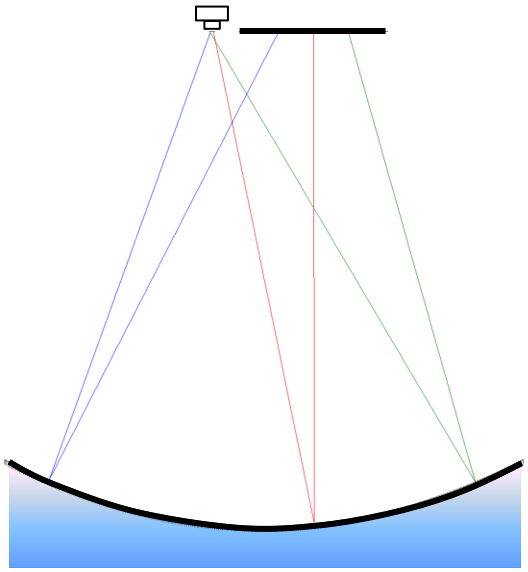
The Camera is focused on the surface of the Test Mirror

Assuming a perfect mirror and known positions of components one can calculate which TV pixels will light up specific portions of the Test Mirror

A deviation from the expected TV pixels will indicate a slope error

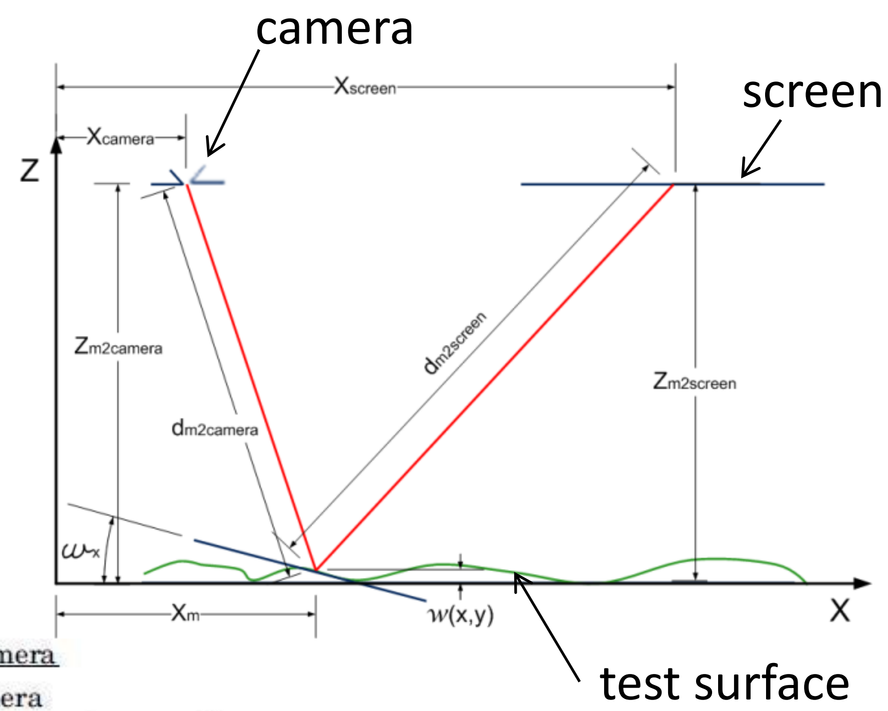
- By knowing the geometry the slope error is calculated

A map of the surface is obtained by integrating the measured slope errors



Principles of Operation

A knowledge of the coordinates of the components (screen, mirror, & camera) is necessary to calculate the surface slopes



$$w_x(x_m,y_m)=\frac{\dfrac{x_m-x_{\text{screen}}}{d_{m2\text{screen}}}+\dfrac{x_m-x_{\text{camera}}}{d_{m2\text{camera}}}}{\dfrac{z_{m2\text{screen}}-w(x_m,y_m)}{d_{m2\text{screen}}}+\dfrac{z_{m2\text{camera}}-w(x_m,y_m)}{d_{m2\text{camera}}}}$$

$$w_y(x_m,y_m)=\frac{\dfrac{y_m-y_{\text{screen}}}{d_{m2\text{screen}}}+\dfrac{y_m-y_{\text{camera}}}{d_{m2\text{camera}}}}{\dfrac{z_{m2\text{screen}}-w(x_m,y_m)}{d_{m2\text{screen}}}+\dfrac{z_{m2\text{camera}}-w(x_m,y_m)}{d_{m2\text{camera}}}}$$

Ref: P. Su et.al. Applied Optics Vol 49, No.23 p4404-4412 (2010)

Principles of Operation

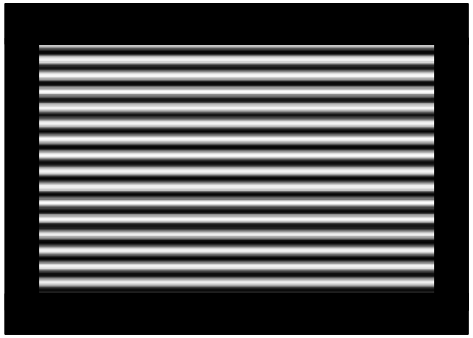
Illuminating one pixel at a time, while effective and unambiguous, would be time consuming and cumbersome

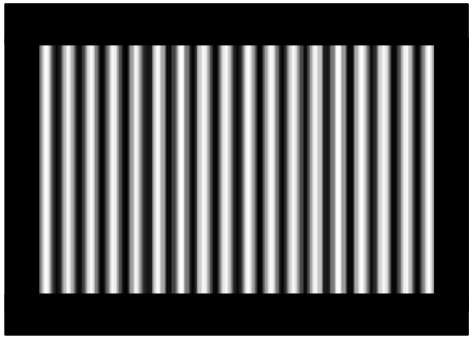
- Yet very powerful for poorly behaved surfaces in the early stages of fabrication

Assuming a reasonably behaved surface (well enough behaved for current interferometry methods) a sinusoidal illumination pattern can be used.

- A series of images are captured between which the fringes are phased

The pattern is then rotated 90 degrees and the fringes are again phased





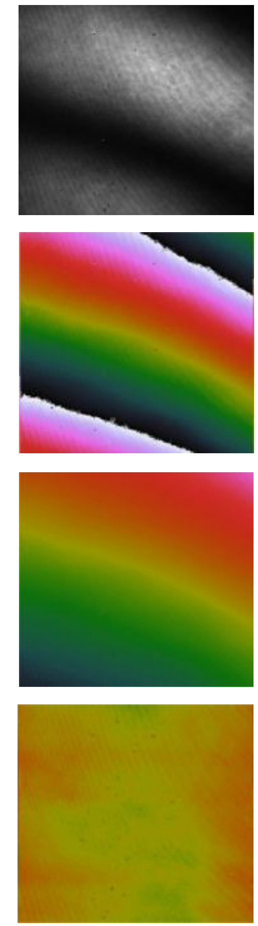
$$I = a + b\cos(2\pi r/p + t)$$

p is the period of the fringes
r is the screen pixel location

Principles of Operation

$$\phi(x,y) = \tan^{-1}\left[\frac{-\sum I_i \sin(\delta_i)}{\sum I_i \cos(\delta_{i)}}\right]$$

$$\delta_i = \frac{i2\pi}{N} \qquad i = 1,\ldots,N$$



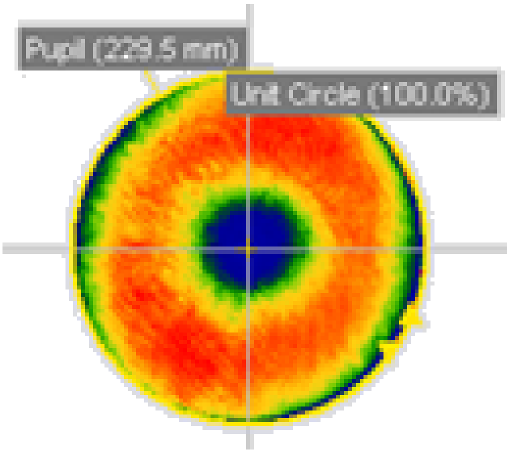
Just as a fringe pattern from a phase shifting interferometer is unwrapped, the phase is calculated as N step phase shifting algorithm
The output is a map of illumination screen locations for each “mirror pixel”

Ref [1]: W. Osten, et. al. ,Proc. SPIE 2860, 2-13 (1996)
Ref [2]: W. Juptner, et. al. ,Pro. SPIE 7405, 740502 (2009)

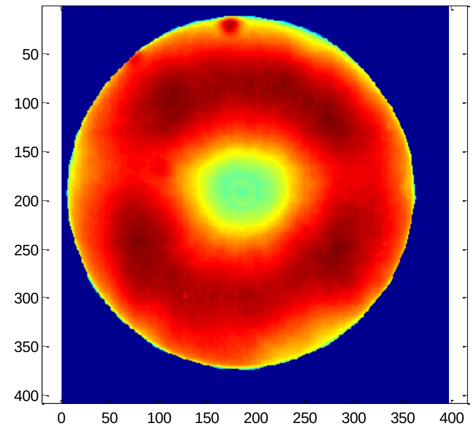
Proven Performance for Concave Optics

The University of Arizona has verified this technology for concave prescriptions

Interferometric Data
26nm RMS



SCOTS Data
26nm RMS



A Million (dollar) Reasons to Test Convex Surfaces with SCOTS Reaching for the Brass Ring

Interferometric tests of Convex aspheres require:

> larger optics

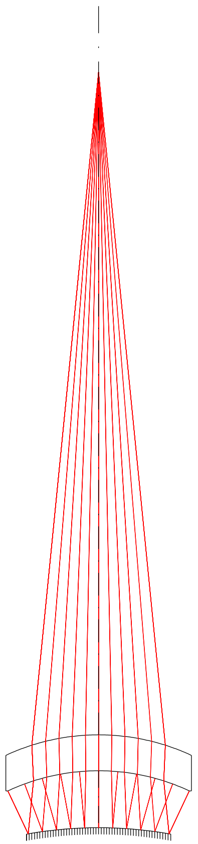
  > Expensive to build - large piece of glass with tight homogeneity requirements

  > Drives long schedules - reference optic needs to be made before testing of the customer's optic can begin

> Stitching Solutions

  > Slower data collection

  > Increased uncertainty for low spatial frequencies



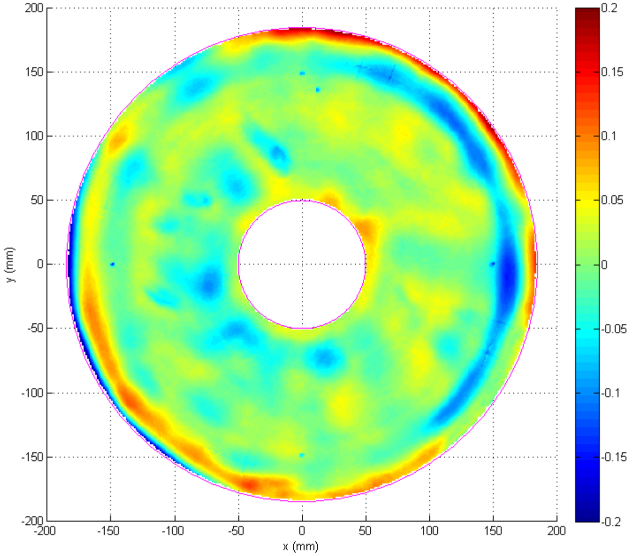
Conventional Hindle shell test

Convex Asphere Measurements

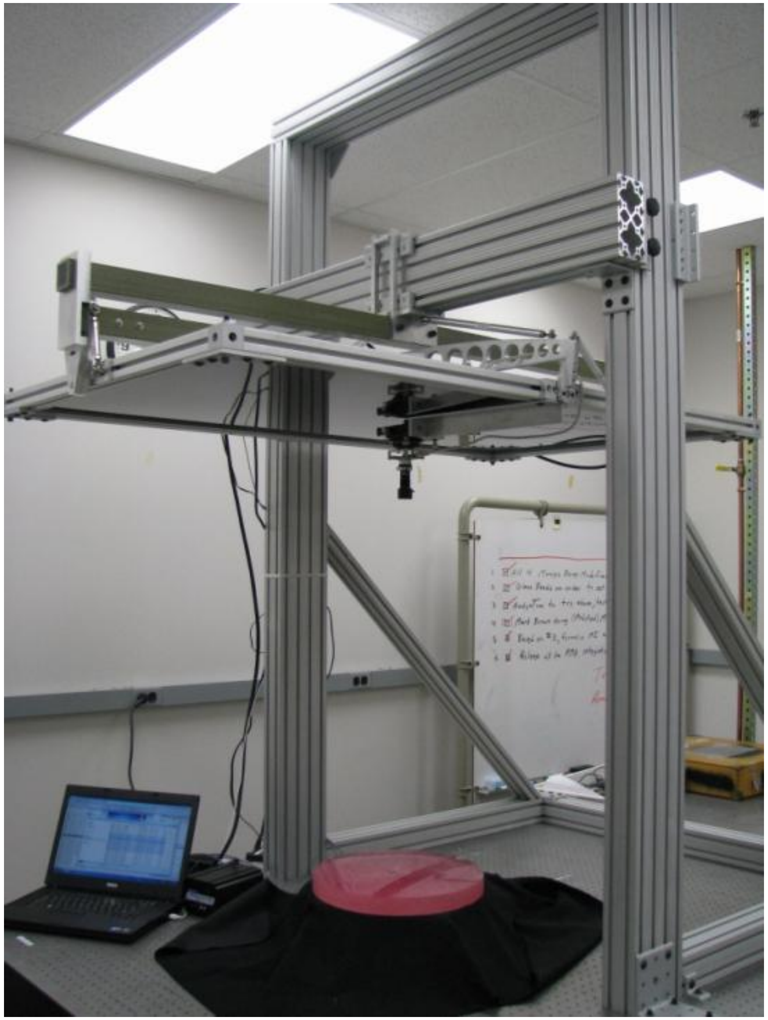
Exelis has a convex asphere that has been used to verify the performance of other test sets

- The surface figure of this asphere is therefore very well known
  - No need to spend time on this program to identify the true surface

42nm RMS

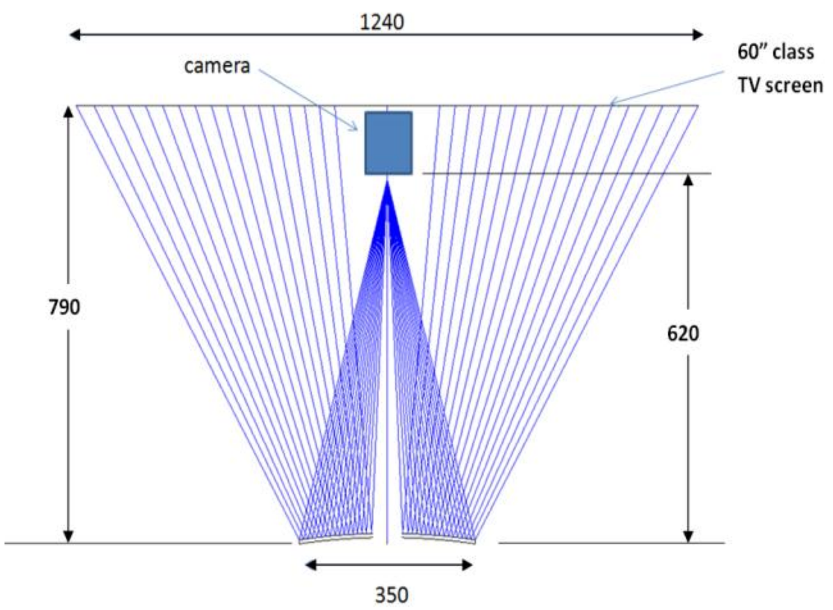


TestBed Design



Convex Asphere Measurements

Surf:Type		Comment	Radius	Thickness	Glass	Semi-Diameter	
OBJ	Standard		Infinity	631.605		0.000	
STO	Standard		Infinity	-11.355		176.483	U
2*	Standard		1360.550	-790.000	MIRROR	176.500	
IMA	Standard		Infinity	-		645.003	



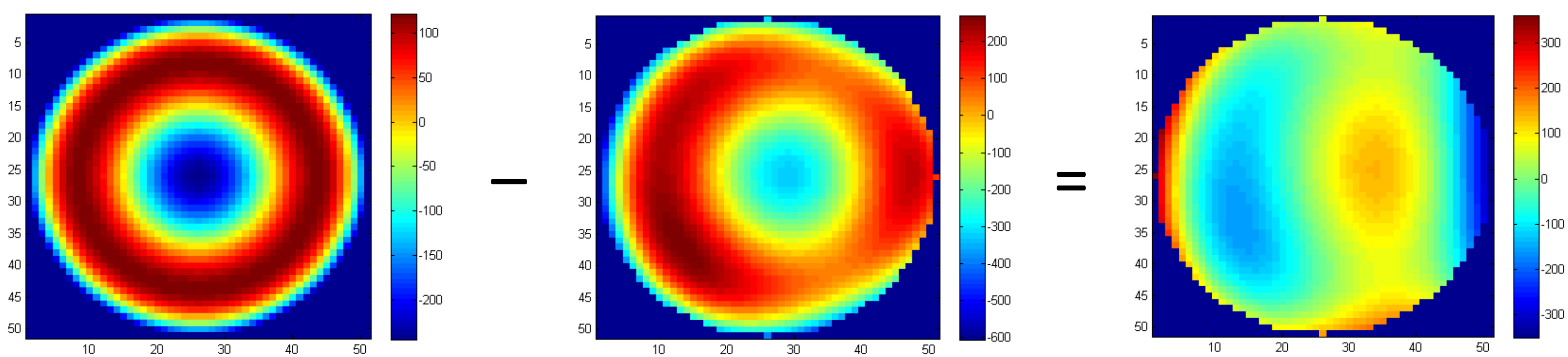
Zemax model of the test configuration

TestBed Uncertainties

The specific mirror prescription has a strong influence on the sensitivities

A sensitivity table was built using the Zemax model

- System alignments were perturbed
- Data from the model was analyzed in the SCOTS software
- Zernike fits to delta maps are used for the sensitivities



Nominal system **Perturbed system** **Sensitivity Map**

TestBed Uncertainty

	Camera X/Y Position	Camera Height (Z)	Camera Pan X/Y	Camera Distortion	Camera Scaling	Screen Height (Z)	Screen Tilt	Total (RSS)
Power	3	300	0	0	0	436	512	529.2
Astigmatism	4	0	0	0	0	0	1205	4.0
Coma	76	0	45	0	0	0	31	88.3
Trefoil	81	0	0	0	0	0	9300	81.0
Spherical	3	10	0	0	10	5	93	15.3
Sec Coma Sec Tref Pentafoil	47	0	0	0	0	0	1960.8	47.0
Higher Order	0	0	0	4.7	0	0	0	4.7
RSS (excluding Power)	120.7	10.0	45.0	4.7	10.0	5.0	9581.0	129.8

Power is ignored because we can use other tools to measure the radius

The other remaining non-axisymmetric terms can be averaged out with a multi orientation test

- The test mirror needs to be well centered on the rotary stage

Final uncertainty should be in the range of 16nm RMS

Convex Asphere Measurements

SCOTS data collection

- The sinusoidal pattern on the illumination screen is reflected off the test mirror
- The shadow of the camera boom is easily seen in these images
- The system is not capable of capturing the entire surface in one image
  - This is resolved by rotating the mirror and collecting multiple data sets
  - Multi orientation tests enable separation of test errors from mirror errors

Convex Asphere Measurements

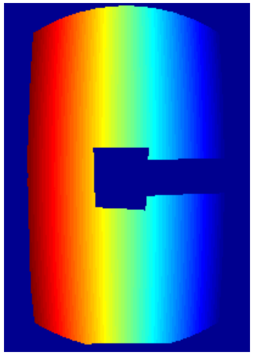
The unwrapped phase maps are the transverse ray aberration maps.

Surface slope maps are then calculated

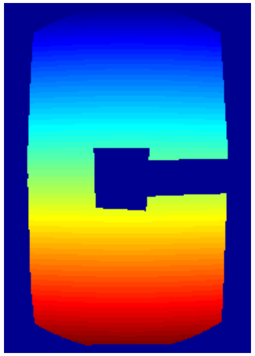
The slopes are then used to create a map of the surface

Much like a non-null interferometric test needs a backout that comes from a model of the system, this system needs a backout

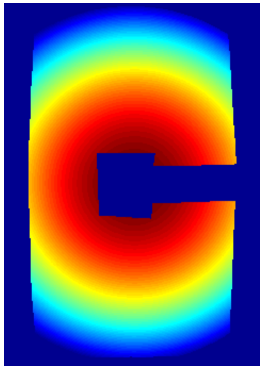
X Slope



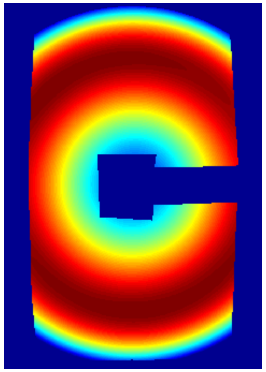
Y Slope



Piston & Tilt Removed



Power Removed



105µm RMS

Convex Asphere Measurements

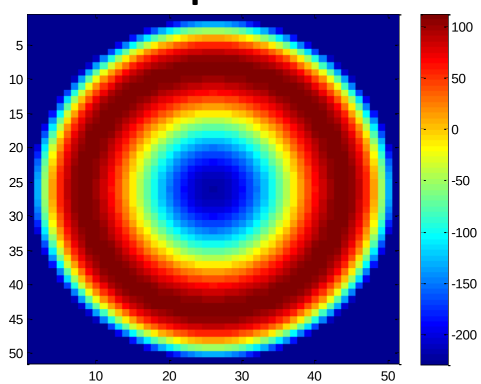
The Zemax model was used to create the system backout

- Analyzed with the same code as used to manipulate the measured data

The final map is NOT in good agreement with the known surface

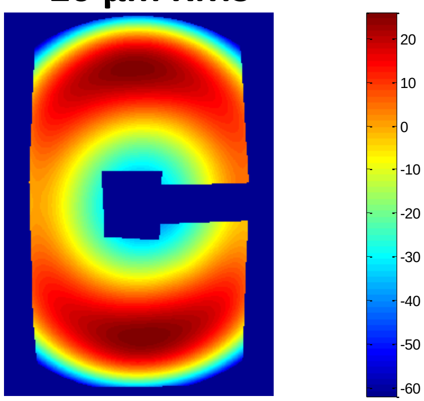
- A perfect surface would result in a flat map
- This surface should have been ~40nm RMS

100 µm RMS



System backout from Zemax model

20 µm RMS



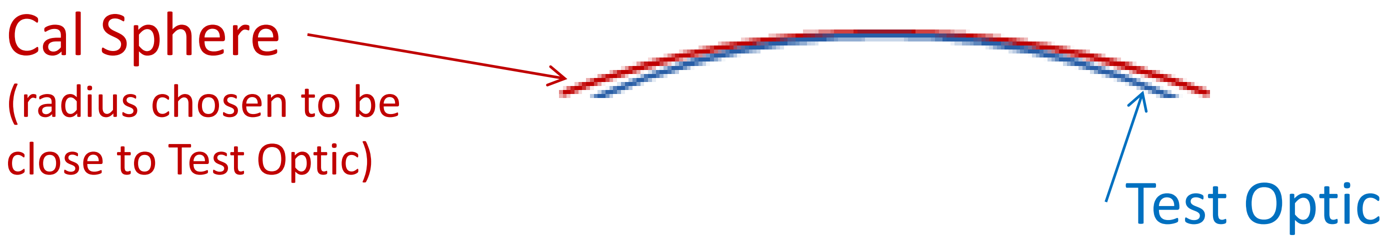
Final Map of Measured Surface Figure Errors

Piston, Tilt, Power, Astigmatism, & Coma Removed

System Calibration

A full system calibration can be used to eliminate the system uncertainties

- This calibration was accomplished by measuring a known surface that was chosen to be close in radius and size to the test mirror
- In taking this approach the data collected from the test mirror can be thought of as a deviation from the calibration sphere
  - Systematic errors will be virtually identical for similar mirror testing geometries



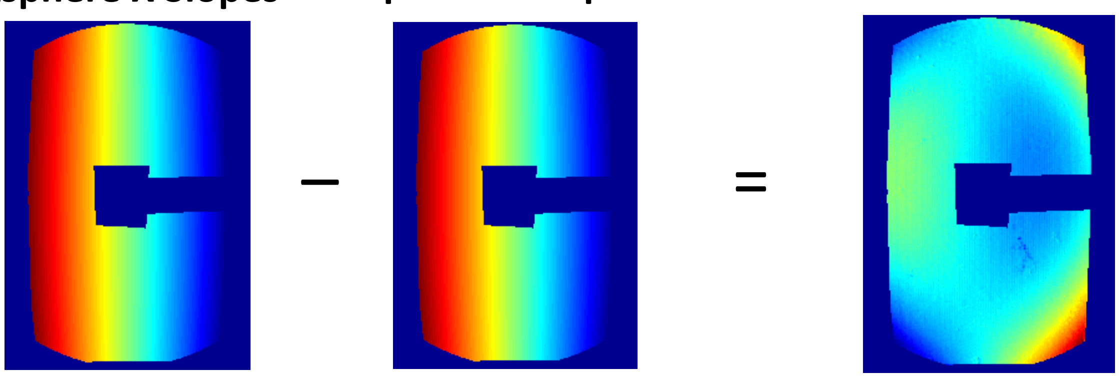
Applying the System Calibration

The calibration is applied at the X/Y slope map stage

Assuming that the calibration sphere is perfect, the sphere slope maps are maps of the system errors

Subtract the slope maps of the sphere from the slope maps of the asphere

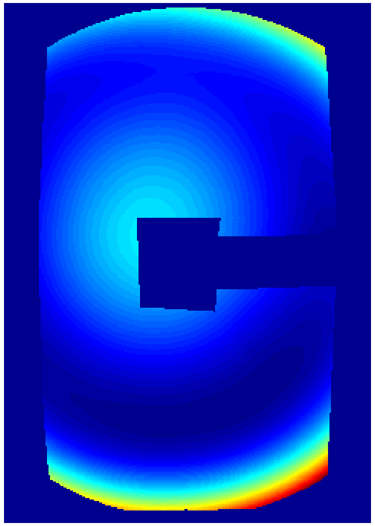
Measured Asphere X Slopes   **Sphere X Slopes**   **Asphere X Slopes**



Applying the System Calibration

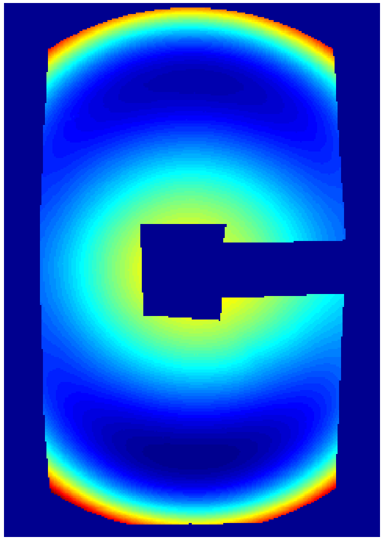
Integrating the new slope maps yields a surface map much closer to the expected result

9.3µm RMS



Subtract tilt, power, astigmatism, and coma

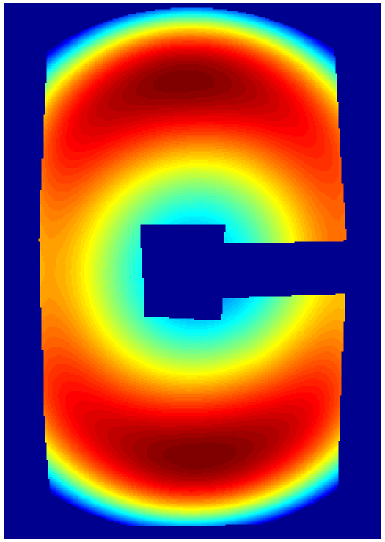
6.4µm RMS



Applying the System Calibration

Without system calibration

20µm RMS

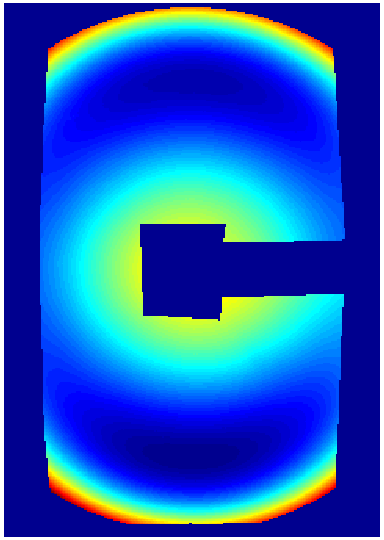


This surface has had the nominal surface removed and only represents the departure from that ideal

This is not a 1:1

With system calibration

6.4µm RMS



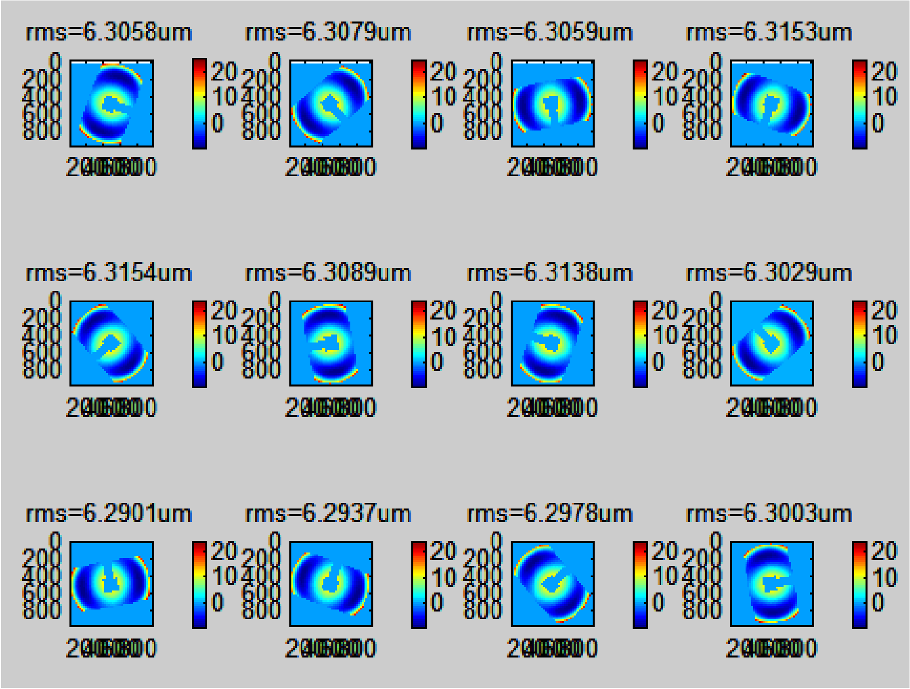
This surface still retains all of the aspheric departure

Results Analysis

Data needed to be stitched to be able to compare to interferometric data

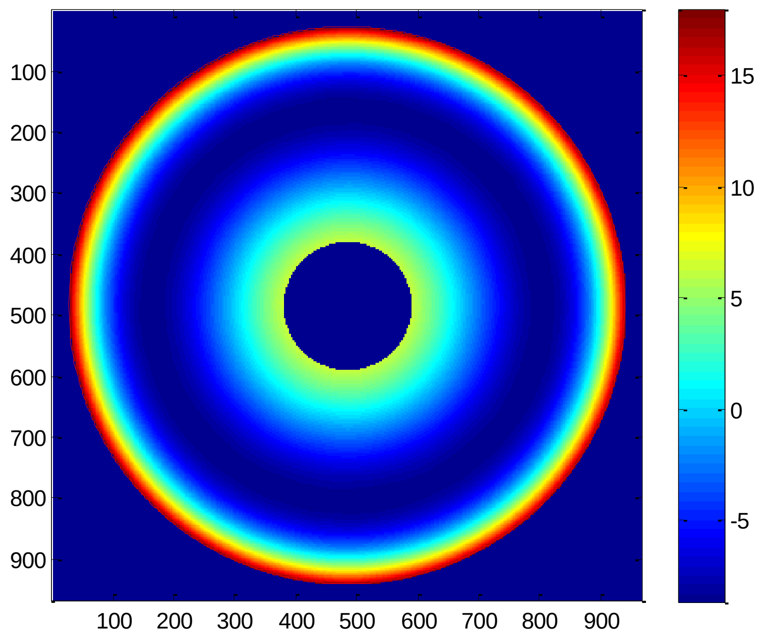
> Data was collected at multiple orientations to cover the full aperture

> The data was then stitched using a proprietary University of Arizona routine



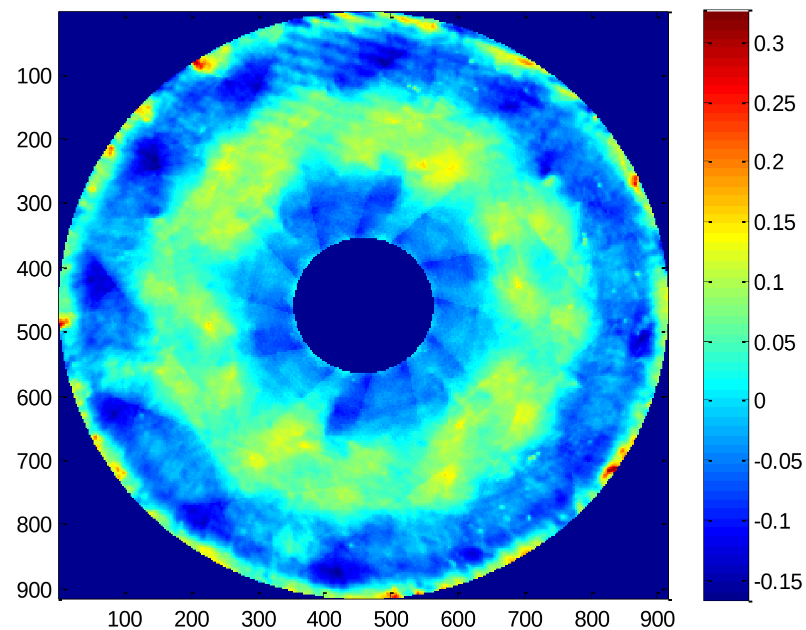
Results Analysis

6.957µm RMS



Initial stitched results

60.6nm RMS

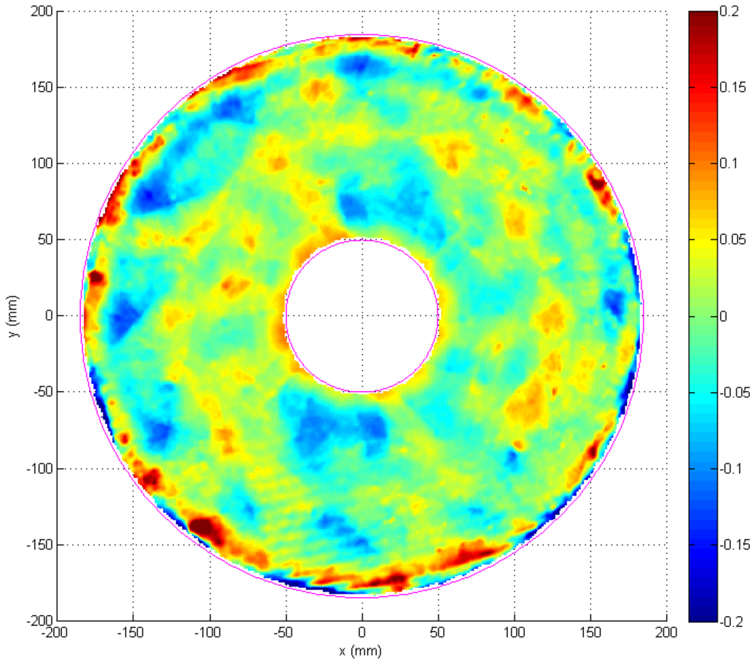


Nominal aspheric departure removed

The source of the remaining spherical aberration is unknown at this time ~46nm spherical

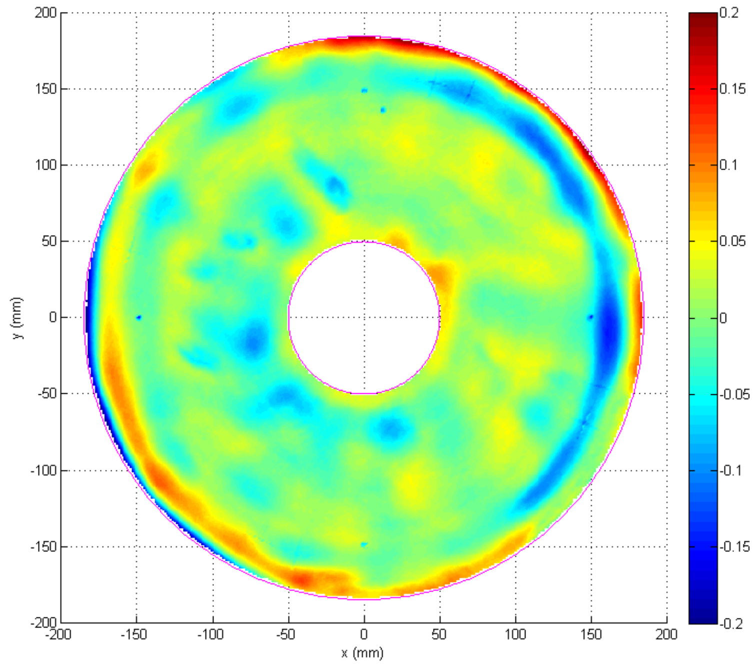
Comparison of Results to Interferometric Data

51nm RMS



SCOTS data with spherical removed

42nm RMS



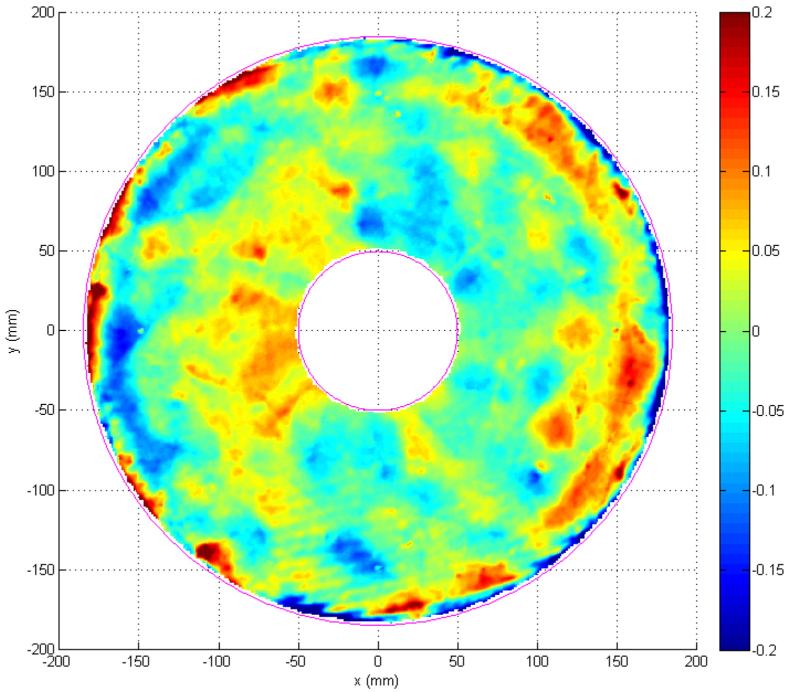
Interferometric data

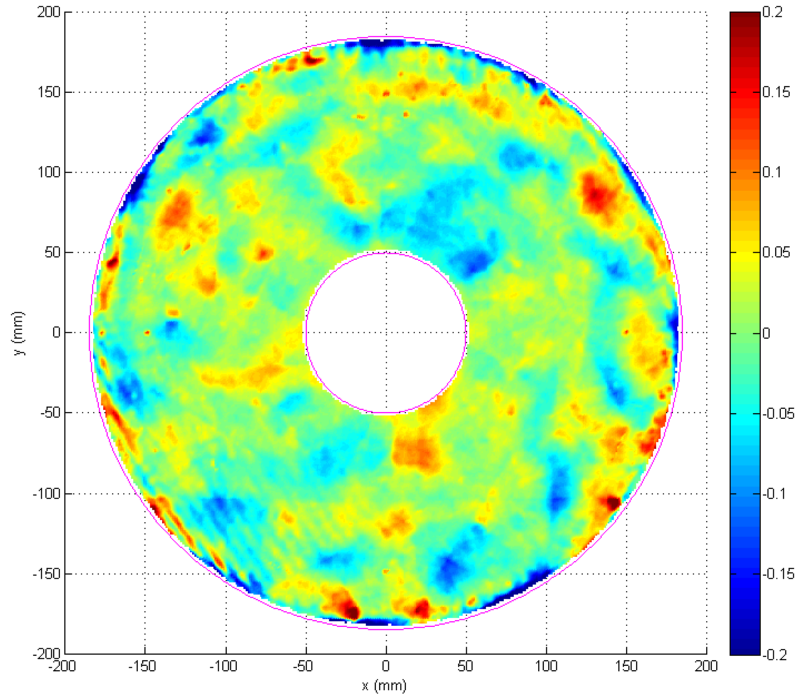
Similarities in data features can be seen

Delta Maps

SCOTS Data Minus Interferometric Data

Rotated to match structure in data	Rotated to minimize RMS
59nm RMS	**48nm RMS**





System Calibration

The system calibration proved effective

- Reduced measurement results from 20µm RMS surface to 60nm RMS surface

Yet the end results still did not fully meet expectations

- The calibration sphere was not as well know as was desired
  - Due to various program constraints better knowledge of the sphere was not accomplished within this study
- We should explore the possibility of using a very good flat for this calibration
  - A flat would be easier to quantify and be more broadly applicable
  - The application of the backout would need to be done differently
  - This would not calibrate everything in the system in one test
    - Screen sag is one example

Summary

The system is much more sensitive to uncertainties when measuring convex surfaces

- Concave surfaces have the advantage of being tested in a (nearly) stigmatic condition

The alignment of the system is critical

- The uncertainties of the placement of the test set components could be improved with a multi-step laser tracker approach

Based on the calculated uncertainty budget SCOTS can get to the desired performance for convex aspheres

Much work still needs to be done to improve the calibration knowledge

Acknowledgments

I would like to thank the following for invaluable input in the development of this project

- James Burge, Ph.D.
- Eugene G. Olczak
- Timothy Lewis, Ph.D.